AD-A049 152 NAVAL RESEARCH LAB WASHINGTON D C F/G 20/5
HARMONIC GENERATION IN ND:LASER-PRODUCED PLASMAS.(U)
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NRL Memorandum Report 3626

Harmonic Generation in Nd:Laser-Produced Plasmas

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October 1977

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Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3626	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 HARMONIC GENERATION IN Nd:LASER-PRODUCED PLASMAS.		5. ~~TYPE OF REPORT~~ & PERIOD COVERED Interim report, on a continuing ~~NRL problem.~~
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 E. A. McLean, J. A. Stamper, B. H. Ripin, H. R. Griem*, J. M. McMahon ~~and S. E. Bodner~~		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D. C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem H02-29A
11. CONTROLLING OFFICE NAME AND ADDRESS Energy Research and Development Administration Washington, D. C. 20545		12. REPORT DATE 11 October 1977
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 18 SBIE 19 AD-E000 057		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) 12 13p. Approved for public release; distribution unlimited. 14 NRL-MR-3626		DDC RECEIVED JAN 31 1978 B
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Sponsored by the Energy Research and Development Administration at the Naval Research Laboratory. *University of Maryland, College Park, Maryland		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Laser harmonics Laser matter interaction Laser absorption Neodymium glass laser Laser spectroscopy		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The fundamental and second through fifth harmonic spectral lines have been observed from the plasma produced when a 75-psec Nd:glass laser ($\sim 10^{16}$ W/cm^2) is focused onto a thick, planar polystyrene target. Both line profiles and relative intensities of these harmonics are given. approx. 10 to the 16th power W/sq.cm.		

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S/N 0102-014-6601

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HARMONIC GENERATION IN Nd:LASER-PRODUCED PLASMAS

There have been many observations of second harmonic light[1-8] emitted from laser-produced plasma. However, there have been no reported observations of third or higher harmonic emission in plasmas generated by a Nd:glass laser, although third harmonic light[9-10] and higher harmonics[11] have been observed from CO_2 laser-produced plasmas. We report here the first observations of the third, fourth, and fifth harmonics lines produced when a high irradiance Nd:laser beam (1.06 μm) is focused onto a target. It is generally thought that integral harmonic emission is generated at or near the critical surface (where fundamental and local plasma frequencies are equal) and, therefore, can yield information on density gradients and electric fields in this region of the plasma.[2,12] (A slower fall-off in the intensity of the harmonics would be an indication of a steeper density gradient or a higher field strength.) Thus, information on the harmonic emission is important in understanding the laser-target absorption process. These emissions may also interfere with diagnostic light probe studies such as shadowgraphy, interferometry, Faraday rotation, etc. which use light at the harmonic frequencies of the incident laser beam. As an example, a time-integrated photograph of third harmonic emitted light (3546 Å) taken through an interference filter (3546 ± 50 Å) is shown in Fig. 1a. The small spatial extent

Note: Manuscript submitted September 28, 1977.

of the emission (~ 5 μm), even though averaged over time and spread by refraction effects, is indicative of a very localized emission region and, perhaps, of steep density gradients near the critical density.

The experimental arrangement is shown in Fig. 1b. One beam (6-10 J) from the NRL Pharos II Nd:laser (1.06 μm) operating at 75-psec pulse duration (FWHM) was focused at normal incidence onto a polystyrene (CH) slab target in an evacuated ($\leq 10^{-4}$ Torr) chamber using an f/1.9 aspheric lens. Prepulses were monitored on each shot and did not exceed 1 μJ in these experiments. The half-energy focal diameter was measured[13] to be 30 μm yielding an average irradiance of $\sim 10^{16}$ W/cm^2. A focal-shift monitor[14] ensured that the target was in focus on each shot. The fractional absorption of laser light was inferred to be ~ 50% by measuring the light backscattered through the focusing lens and outside the lens with calorimeters.[15] Simultaneous observations of the harmonic light were made with a 3/4-m Czerny-Turner mount spectrograph (resolution in first order ~ 1 Å for a slit width of 100 μm) and an interference filter - photovoltaic silicon photodiode combination (E.G.G. UV-100 B biased to - 22½ V). These detectors viewed the target at 45° to the target normal and in a (horizontal) plane at 45° to the plane of the incident laser's electric field. The rise time of the photodiode and recording oscilloscope was ~ 2 nsec, and the photodiode was proved linear in the range discussed here. Care was taken to block the higher order spectra from entering the spectrograph. An achromatic optical train was achieved by using a spherical and a flat mirror to focus the plasma onto the spectrograph slit. Three types of film were used in the spectrograph to cover the range of wavelengths and sensitivities encountered in this experiment, i.e., Kodak I-Z plates, Kodak Royal-X Pan, and Polaroid Type 57. (All spectra required only one shot.)

Microdensitometer scans of representative time-integrated spectral profiles for the fundamental emission, ω_o, and the integral harmonics through the fifth, $5\omega_o$, are shown in Fig. 2. The wavelength of each harmonic is indicated by a vertical dashed line. The peak of the fundamental line is blue-shifted by about 13 Å. If the shift (13 Å) is a Doppler shift, this would correspond to an average outward velocity of the reflecting surface of 3×10^7 cm/sec. A blue shift of the fundamental has also been observed by others.[10] However, the centroids of the rest of the harmonic lines are red-shifted. It appears that the scattered fundamental line is produced by a different mechanism or spectral region than that which produces the harmonic lines. The $5\omega_o$ line at 2128 Å is just resolved above the plasma continuum. To observe this harmonic line, the spectrograph slit was opened to 500 μm so that the resolution was reduced to ~ 5 Å. Because of the expected low signal level, we did not attempt to observe $6\omega_o$ at 1773 Å. All of the observed harmonic spectral widths are large compared to that of the incident laser width (~ 1 Å).

The spectral widths (FWHM) for the second, third, and fourth harmonics in wavelength and frequency units (to facilitate a comparison with theory) are shown in Table 1. It is seen that the spectral half-widths in frequency units change at most by 60%, whereas the half-widths in wavelength units change by almost a factor of 3. The observed spectral broadening thus involves mechanisms other than Doppler broadening (either due to random or non-local mass motion) such as instabilities and magnetic fields.[16]

Assuming shot-to-shot reproducibility of the over 150 data shots, relative (total) intensities of the harmonics measured with the silicon photodiode-interference filter are shown in Fig. 3. These values of relative intensity are corrected for the transmission and the band pass of the filters and the spectral responsivity (given by the manufacturer) of the silicon photodiode. The error bars indicate the estimated error in the measurement due to the spectral responsivity uncertainty and the signal-to-noise ratio. There is a large decrease ($\sim 2 \times 10^2$) in the intensity of the second harmonic relative to the reflected or scattered fundamental; however, the next three harmonics decrease in steps of less than a factor of 10. These ratios of harmonic line intensities are the same (within a factor of 5 over a range of 5 orders of magnitude) as the corresponding harmonic intensities reported by the National Research Council Group[11] in Ottawa, Canada, using a CO_2 laser at an irradiance of $I = 10^{14}$ W/cm^2. This fact suggests that a comparable interaction takes place in Nd: and CO_2: laser irradiation which scales as $I\lambda^2$.

In summary, we report emission spectra and relative intensities of the fundamental and second through the fifth harmonics of the incident laser line when a Nd:laser (10^{16} W/cm^2) is focused onto a

CH slab target. The emission is sufficiently intense that the contrast in diagnostic probe studies at these harmonic wavelengths would be adversely affected. (This difficulty has been obviated at NRL by shifting the probe wavelength using a Raman cell to a nonharmonic wavelength[17].) Although the present theories of optical absorption of intense light in plasma have not yet predicted the ratios, widths, and shifts at the higher harmonics, these harmonics should be directly related to the absorption process and would aid in estimating density gradients and electric fields produced in the absorbing layer. Hopefully, these experimental results will stimulate the appropriate theoretical explanations. An interesting result of this study is that the spectra and relative intensities of the harmonics produced in Nd:laser-target interactions at 10^{16} W/cm^2 are strikingly similar to recent results[11] found in CO_2 laser-produced plasmas at 10^{14} W/cm^2.

We would like to acknowledge the excellent technical assistance of E. Turbyfill, T. DeRieux, and A. Unzicker. Also, we would like to thank R. Decoste, R. H. Lehmberg C. M. Armstrong, and F. C. Young for useful conversations and assistance and R. W. Whitlock for help in analyzing the data.

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a. Work sponsored by the U.S. ERDA.

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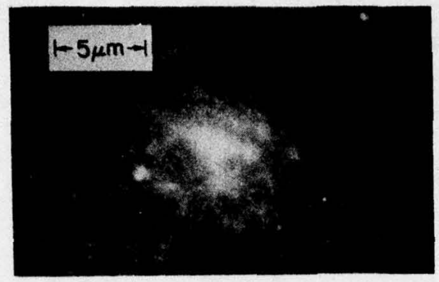
Table 1 — Spectral half-widths (FWHM) of the harmonics in frequency and wavelength units. The estimated error from the photographic plate calibration and a small number of representative shots is ± 10%.

HARMONIC	$\Delta\omega_{FWHM}$ [rad sec^{-1}]	$\Delta\lambda_{FWHM}$ [Å]
$2\omega_o$(5320 Å)	1.9×10^{13}	29
$3\omega_o$(3547 Å)	1.7×10^{13}	11
$4\omega_o$(2660 Å)	2.7×10^{13}	10



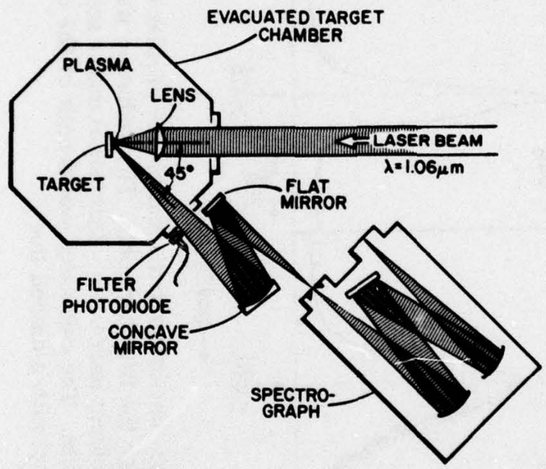


Fig. 1 — a) A time-integrated photograph of the third harmonic light (3546 Å) emitted tangential to the target surface when a 75-psec, ~ 10^{16} W/cm^2 laser pulse strikes a CH_2 plane target. The laser beam was incident from the left. A 3547 Å interference filter with a bandwidth of 50 Å was used in front of the camera. b) The experimental arrangement.

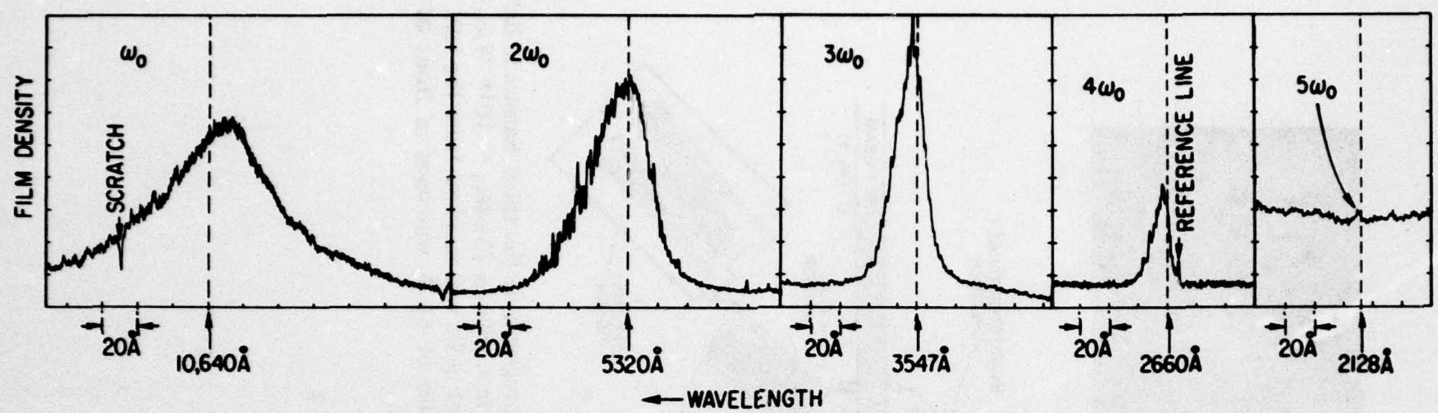


Fig. 2 — Representative time-integrated spectral line profiles are shown for the fundamental through the fifth harmonic. This radiation was observed at 45 degrees from the incident laser beam. Extraneous marks are indicated on the ω_o and $4\omega_o$ profiles. The calculated wavelength of the center of each spectral line is indicated with a dashed line.

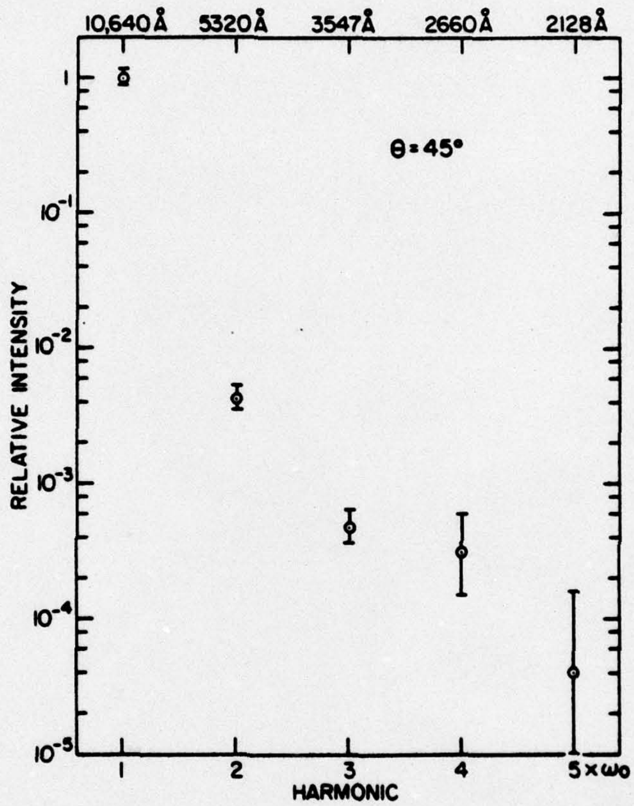


Fig. 3 — Intensities of the harmonics relative to the fundamental emission at 45° to the incident laser beam. The error bars are estimated from the spectral responsivity uncertainty and the signal-to-noise ratio.